

Method for flow improvement and reduction of fouling in process equipment

Technical field

This invention relates to a method and apparatus for improvement of flow rates and reduction of fouling in process equipment such as for instance heat exchangers where fluids are flowing in single or multiphase. An improved flow rate will cause that the heat exchanger becomes more efficient, i.e. a lower deposition rate and a higher removal rate of inorganic agents. The fluid may be a pure fluid, colloidal fluid or contain inclusions in the form of particles.

Background

The formation of deposits (foulants) on heat transfer surfaces is a major cost factor in the installation and operation of heat exchangers. The accumulation of deposits on the heat transfer surfaces often results in reduced heat transfer rates and may cause other problems of operation. Heat exchangers are used in almost all kinds of industries including process industry and oil industry. Consequently, the fouling problem is present in almost all kinds of industries. The total fouling related costs for the industrialized world are estimated to be in the order of 40,000 million dollar U.S. per year [1].

Despite the enormous costs associated with fouling; only very limited research has been done on this subject. Reliable knowledge of fouling economics is important when evaluating the cost efficiency of various mitigation strategies. Despite the great practical experience with fouling preventing methods, and the results from ongoing research, the fouling in heat exchangers is still a great problem. Therefore, there is a great need for development of new and more effective methods to reduce or prevent the rate of fouling in heat exchangers [1].

Prior art

There are known several chemical and physical/mechanical methods for reducing/- removing the scaling and/or fouling problem in systems where water and/or other process liquids are flowing. However, their efficiencies vary a lot from method to method, and they also suffer some disadvantages.

One widely known and long used approach to handle the problem with scaling and/or fouling in heat exchangers is the so-called chemical methods where one or several agents is(are) added to the liquid(s) in the system in order to increase the solubility of the compounds that forms the scaling and/or fouling. These methods are known to be effective in both preventing formation of scaling/fouling and to dissolve already formed scaling/fouling. In the case of heat exchangers, it is common to either add the agent(s) to the process fluid, which often reduce the quality of the produced products, or to the cooling/ heating medium which may represent a pollution problem. These problems can be solved by performing

periodic cleansing procedures where the heat exchanger is disconnected from the process line and flushed with a cleansing liquid. But in this case, the normal operation of the process must obviously be stopped with attendant increased operating costs. As a result, chemical treatments are often found to expensive and labour demanding to be an acceptable solution to the problem with scaling/fouling.

It has therefore been an increased focus on preventing, and in some cases even reversing scale formation by applying an electric and/or magnetic field to the flowing water and/or process liquid. It is generally assumed that the cause of this effect is that exposing the water/liquid flow to electromagnetic fields may generate nuclear clusters in the bulk liquid that act as seed crystals, such that the scale-and/or fouling forming compounds are precipitated as solid suspended particles in the bulk liquid and then carried along with the bulk stream. An example of such technology is disclosed in EP 0720588, where water is subject to radiofrequency signals in order to prevent scale formation. It has also been reported that magnetic fields may be useful for preventing lime scaling in much the same manner as electric fields. An example of such technology is disclosed in US 4 278 549. In WO 94/02422 it is described a device and method where the water flow is exposed to microwave radiation which frequency is tuned to be absorbed by one or several of the following ions/compounds of the water: Ca^{2+} , CO_3^{2-} , HCO_3^- , CO_2 , CaHCO_3^+ , H_2CO_3 , and H_2O . It is believed that the electromagnetic radiation causes the precipitates to form on a micro-scale in the bulk flow to be carried away instead of on the surfaces of the process equipment.

In the case of scaling, or build up of precipitated CaCO_3 , the effect of such electromagnetic treatment methods is thoroughly discussed by American Petroleum Institute [2] and scientists [3-10]. The results obtained from various experiments and tests are controversial. Some results show that the magnetic and/or electric fields reduce precipitation of calcium carbonate, others do not. However, the way the magnetic/electric fields are introduced, and the magnitude of the fields vary from experiment to experiment. Consequently, the parameters that describe the exposure system also vary from experiment to experiment. In addition, no quantitative relationship between the parameters that describe the magnetic/electric fields and the effect on the fluid flow system has been reported. Therefore, by this lack of scientific knowledge, it is almost impossible to fully control of the effect of those methods on deposition of calcium carbonate.

However, theoretical and experimental investigations have been performed to understand the mechanisms of fouling and to reduce the rate of fouling in heat exchangers. The mechanisms include crystallization fouling, particulate fouling, biological fouling, chemical reaction fouling, corrosion fouling, and freezing fouling. However, it is unlikely that fouling is exclusively due to a single mechanism, but in many situations, one mechanism will be dominant. Results from

the investigations on the various mechanisms involved in the fouling process have revealed that the following three parameters are of greater significance than others concerning control of the fouling process: the temperature gradient across the heat exchanger surface, the concentration of the foulant, and the flow velocity at the heat exchanger surface [11,12]. The latter effect is exploited in this invention.

Objective of the invention

The main objective of this invention is to provide a method and apparatus for improving/enhancing the flow velocity in process equipment where a process liquid is flowing in order to reduce/eliminate the problem with fouling.

Another objective of this invention is to provide a method and apparatus for improving/enhancing the flow velocities at the heat transfer surfaces in heat exchangers in order to increase the efficiency of the heat exchangers and at the same time reduce/eliminate the problem of fouling.

Summary of the invention

The objectives of this invention are obtained by the method and apparatus as defined in the appended claims and/or the following description of the invention.

The present invention is partly based on an effect that was discovered by the present inventor, and which formed basis for another invention that is protected by for example US 6 334 957 or the corresponding EP 1 021 376. This patent family gives a thorough description of the effect, and is therefore included by reference in this application. Here, it will only be given a short summary of the effect:

- When a fluid flows through a pipe, there will be torn loose electric charges at the wall of the pipe due to shear forces in the boundary layer. This will give rise to an electric potential (the electric friction potential) at the pipe wall that will attract and retain charged particles, ions and dipoles in the fluid, and thus induce a friction force that reduces the flow velocity of the liquid in the pipe. This contribution to the flow friction is often referred to as the electric contribution to the friction factor.

The invention disclosed in US 6 334 957 is based on that this build-up of electric charges at the fluid-solid boundary can be counteracted by imposing a DC electric potential on the pipe/duct wall that exactly balances the build-up of electrical charges on the wall. Then the electromagnetic force that attracted the ions and polar molecules will diminish, and the ions and polar molecules may freely follow the flowing fluid. In other words, the electrical contribution to the friction factor becomes zero, and the average flow velocity of the fluid will consequently increase, especially at the liquid-solid boundary (at the wall). US 6 334 957 discloses a

regulation method that ensures that the imposed DC potential exactly opposes the electric friction potential at all times and an apparatus for performing the method.

The present invention is based on the discovery that the elimination of the electric friction factor for liquids flowing in pipes, heat exchangers, reactors and all other forms of industrial process equipment, is also a convenient and effective mean for preventing and in some cases even revert already formed fouling and scaling. That is, by enhancing the flow velocities at the surfaces of heat exchangers and other process equipment where fluids are flowing, one will reduce the deposition rate of precipitates thus reduce/prevent formation of scales, fouling, and any other types of solid deposits on the walls of the heat exchanger/process equipment. This is believed to be due to that the enhanced flow velocity at the solid-liquid boundary (the heat exchanger wall) will carry away a larger portion of the solid precipitates in the bulk stream.

It is surprising that the effect of the modest increases of the flow velocities that are being obtained by removing the electric contribution to the flow friction factor is able to give an effective reduction of the deposition rate of precipitates such that the invention becomes an efficient tool for handling the problem of scaling/fouling in heat exchangers and other process equipment. Not to say that these modest velocity increases, usually in the order of 1-10%, are also able to increases the shearing action at the deposit-fluid interface sufficiently to remove already formed deposits.

This surprising finding gives a substantial benefit over prior art methods which exploits electromagnetic fields/potentials to prevent fouling/scaling, since the prior methods are focused on that the electromagnetic fields/potentials must be sufficiently strong and act on the bulk liquid in order to enhance the nuclear clustering and precipitation of the scale and/or foulant forming compounds in the process liquid such that the precipitates will be carried away with the bulk flow. But in this case, one will inevitably alter the chemical conditions in the process fluid and may ionise one or more of the liquid compounds or electrically induce one or more electrochemical reactions in the process fluids. Thus, the prior art should be used with care in process industry in order not to induce detrimental side effects in the process. Another unwanted side-effect of these prior art methods is that the employed electromagnetic fields/potentials are almost certain to be of a different magnitude than the electric friction potential, such that the imposed potential will almost certain create a new electric friction potential that may very well be larger than the natural occurring friction potential. This will then slow the flow velocity, which enhances the deposition rate of precipitates. This may be one explanation of why many prior art methods are encumbered with instability.

In the present invention, the imposed electric potential shall exactly counter-balance the natural occurring electric friction potential of the flow. Thus these potentials

will cancel each other such that no electric fields will be felt by the process liquid. Consequently, there will be no risk of inducing any electrochemically alterations of the processes in the flowing process fluid, including alterations of chemical equilibriums, ionising compounds, creating radicals, induce unwanted chemical reactions etc. The naturally occurring electric friction potentials are usually small, in the order plus/minus a few Volts or less, such that one can manage with much less powerful and thus energy efficient fields than in prior art methods. The method according to the invention will therefore be absolutely risk free, both in terms of electrochemistry and handling safety, such that it becomes suited for all thinkable processes, no matter which process liquid that flows through the process equipment.

Another benefit over prior art is that the invention is based on scientific knowledge, such that the method according to the invention will be fully controllable and give consistent results. A further advantage is that the invention represents no pollution problem since no matter is added or removed when implementing the invention and no chemical reactions are induced in the process fluids that may cause unwanted detrimental effects on the process and/or the environment.

In the case of process liquids containing chemically active components, there will normally be another naturally occurring potential that must be taken into account. When a metal (e.g. heat transfer surface) is immersed in a solution (fluid), an electrical potential between the surface of the metal and the solution is established, i.e. the surface is electrified. Most of the metals will normally be negatively charged, and the electrical potential can be measured in relation to a reference cell (e.g. a standard calomel reference cell, SCE). The potential is named the corrosion potential. If the surface is electrified, an additional adhesion appears which is caused by the attractive forces between electrical charges on the surface and the counter-ions or/and dipole molecules in the fluid [13]. This phenomenon represents an additional contribution to the electric friction factor for the fluid flow at the heat transfer surface, which also should be countered by the imposed DC-field. Thus, in this application, the term electric contribution factor means the combined effect of the corrosion potential and the fluid flow friction potential on the total friction factor for the fluid flow.

The invention is related to all kinds of heat exchangers (HE), including air-cooled HE, plate and frame HE, compact HE, shell and tube HE, double-pipe HE, spiral HE, shell-and tube condensers, air-cooled condensers, plate and compact condensers, direct contact condensers, cooling towers, steam generators, boilers, and evaporators. The invention is also related to either the process fluid side or cooling/heating medium side of the heat transfer surface, or both. Also, all other types of industrial and non-industrial process equipment where process liquids are flowing and where scaling/fouling may pose a problem are included.

Thus is summary; the inventive idea is to employ a DC electric potential that exactly counteracts the combined build-up of an electric potential due to the friction from the flowing fluid and the corrosion potential. Thus the electrical potential across the boundary layer (at the liquid-wall interface) is reduced to zero such that the electric contribution to the fluid flow friction at the surface is reduced to zero, and consequently, a maximum increase in the flow rate near the surface will be achieved, which again leads to a reduction/elimination of the deposition rate of suspended precipitates. The naturally occurring potentials at the liquid-solid interface will be less than ± 5 V, but typically less than ± 2.5 V, and often in the order of ± 1.0 V or less.

In order to put the inventive idea into practice, the inventive method may be implemented in a device comprising a control unit which ensures that the imposed DC-potential exactly counters the naturally occurring potential at the liquis-solid boundary. The control unit comprises three parts: a measuring/calculator unit, an electrical DC-potential generator, and a regulator. These components are of conventional nature and need no further description. A similar system is thoroughly described in US 6 334 957 or the corresponding EP 1 021 376. The regulation unit calculates the magnitude of the imposed DC-potential due to information of measured fluid properties upstream of the part of the pipe/duct that is exposed to the DC field, and where that the measured fluid properties may be one or more of the properties contained in the group comprising average flow velocity, corrosion potential, pH, concentration of specific ions contained in the fluid, electrical conductivity, pressure, and temperature.

Detailed description of the invention

The invention will now be described in more detail under reference to a preferred embodiment of the invention.

A preferred embodiment of the invention, when implemented on a shell and tube heat exchanger of is shown schematically in Figure 1. The arrows indicate the flow directions. The invention 1 is connected to the heat exchanger 2 by two or more connectors of conventional type (not shown in the Figure). One connector is connected to a ring 4 in the inlet for the cooling/heating medium 3 which is electrically insulated from the rest of the system. One connector is connected to a ring 7 in the inlet for the process fluid 6 which is also electrically insulated from the rest of the system. A third connector is connected to the heat exchanger itself at the point marked 9. If the invention is used for flow improvement of the process fluid, the connecting point 9 will be at the outlet for the process fluid 5. For the improvement of the cooling/heating medium flow, the connecting point 9 will be at outlet 8. For the flow improvement of the cooling/heating medium, ring 4 is used, and for the process fluid, ring 7 is used.

When the invention is switch into measuring/calculator mode, the set point for the regulator is determined, as described in the following:

The estimation of the set point is based on capacitance measurements. The capacitance is measured between the ring 4, or 7, and the heat exchanger 9 itself by the alternating current method, as a function of the applied DC-potential. Its positive and negative ends are connected to 9 and 4, or 7, respectively. The potential at which the capacitance shows a minimum value, corresponds to the un-electrified condition of the heat exchanger, and is the particular DC-potential used as set point for the regulator. When the invention is switch into working mode, the electrical DC-generator applies the potential between 4, or 7, and 9, and is controlled by the regulator.

Verification of the invention

In order to verify the ability of the invention to reduce deposition of precipitates, a colloid solution of calcium carbonate and barium sulphate in flowing water were made and experiments performed to investigate the deposition rates on a titanium surface. The calcium carbonate and barium sulphate is dispersed (colloid state) in the flowing fluid passing the titanium plate.

EXPERIMENTAL

Solutions

Preparation of the colloid solution of calcium carbonate and barium sulphate: 1 l of 0.00025 M BaCl₂ and 1 l of 0.00025 M CaCl₂ is mixed, and then 2.5 ml of 1 M Na₂CO₃ is added. Finally, 25 ml of 0.01 M Na₂SO₄ is added. In this way a colloid solution of calcium carbonate and barium sulphate is obtained. For fresh solution and room temperature, light scattering measurements performed at different wavelengths give the size calcium carbonate and barium sulphate particles equal to about 50 nanometres. In two-three days these particles reach the size of about 100 nm. Further growth of the size leads to the transformation of the colloid into suspension and the precipitation of calcium carbonate and barium sulphate is observed. Then the colloid solution is replaced by newly prepared solution.

During the experiments carried out at 38°C, the growth of the size of the particles and the precipitation was much faster. Therefore, every day a new solution has been used.

During the measurements, the content of calcium and barium was controlled by atomic absorption spectroscopy.

Flow system

Schematic representation of liquid flow system is presented in Fig. 2. The tube is in the loop which contains two reservoirs with simulated fluid and the peristaltic pump (P). The flow velocity is controlled by the height (H), while the temperature of

liquid is controlled by a thermo reservoir 2. This reservoir also serves for avoiding the periodic pressure changes which arise during the work of the peristaltic pump and which can influence the frequency of quartz crystal oscillation.

Electrodes and Instrumentation

The 5 MHz AT-cut 15 mm diameter and 0.3 mm thick quartz crystals were used. Both sides of crystals were coated with titanium by cathodic sputtering. The decrease in frequency change is linearly related with an increase of electrode mass. The fundamental frequency of quartz crystal (5 MHz) and the geometric area of a circular titanium region in the centre of the crystal (0.2 cm^2) give the EQCM mass sensitivity equal to $25 \cdot 10^{-9} \text{ g Hz}^{-1} \text{ cm}^{-2} = 25 \text{ ng Hz}^{-1} \text{ cm}^{-2}$. These coated working quartz crystals (QCM1, QCM2 and QCM3, see Figs. 3 and 4) were glued into cylindrical holders, which were affixed to the tube in three different ways, see Fig. 3. One side of the crystals were exposed to the solution in the tube and served as working electrodes (QCM1, QCM2 and QCM3, see Figs. 3 and 4). Another side of these crystals faced the air.

The working quartz electrodes were inserted into three separately controlled oscillators - QCM drivers (Fig. 4) configuration of which allows the working electrodes to be grounded. Home-made voltammetric and frequency measurement system was used (Fig. 4). In this system, a high precision frequency counter performs a measurement with accuracy in 0.1-0.2 Hz for about 5 MHz frequency in 3 ms.

During the measurements, the same potential was applied simultaneously to all three electrodes and the changes of the frequency of these quartz supported electrodes with time were separately recorded for 600 s. Then the same experiment was repeated for another potential. In such a way, the potential range from 1 V to -1 V vs. the standard hydrogen electrode (from 0.8 V to -1.2 V vs. the silver/silver chloride/saturated KCl electrode) with 0.1 V increments was investigated.

Results

1. Measurements in colloid solution at flow rate 3 l/min (Re=1300) and room temperature (22°C)

The results of these measurements are depicted in Figs. 5-9.

Low rates observed in fresh colloid solution at the most positive potentials (Fig. 5) can be explained by very small size of the particles (less than 50 nm). During the measurements they were growing (growing was followed by the light scattering technique). That could be the reason for the rate growth when the potential is changed in negative direction but still remains in positive region. When the experiments were repeated next day and on the third day in the same solution, in

positive region the potential influence on the mass deposition rate is smaller (Figs. 8 and 9).

In the negative potential region, the clear potential influence is observed - mass deposition rate is noticeably decreased (Figs. 5, 8 and 9)

Fig. 8 - the same solution and the same conditions of the measurements as given in Fig.5 but the measurements were performed the next day after the experiments, the results of which are presented in Fig 7. The size of particles is approximately 100 nm and still growing, though much slower. The data presented in Fig. 8 show the influence of the potential (growth effects are small). Fig. 9 - solution turned to be more opalescent, the size of particles is larger than 100 nm and solution turned to be more opalescent (white colour of the solution is visually observed).

The rates of mass deposition onto these electrodes were very small and similar for the first two days (Figs. 6 and 7). The measurements, repeated on the third day (the data for bottom electrode are presented in Fig. 9) revealed some similarity to the behaviour of bottom electrode, though the absolute values of the rates are noticeably smaller.

2. Measurements in colloid solution at increased flow rate 4 l/min (Re=1700) and room temperature (22°C)

The results of these measurements are depicted in Figs. 10-12.

Decrease in deposition rates, observed at higher flow rates (Figs. 10 and 11), may be related with "washing" of particles from the electrode surface.

Both experiments 1 and 2 are carried out at laminar flow (the Reynolds numbers are 1300 and 1700, respectively). At laminar flow, the friction factor decreases with increasing Reynolds number. The decrease in deposition rates, observed at higher flow rates (Figs. 9 and 10), may be related with lower friction factor.

Conclusion

The results show that the deposition rate of calcium carbonate and barium sulphate on an electrode surface depends on the applied electrical DC-potential within the range of 0.8 - 1.0 V (Ag/AgCl₂ reference electrode). Within certain ranges a decrease in the deposition rate is observed, while an increase is observed in other ranges.

The results show that the deposition rate decreases with higher flow rates, which indicates that the effect, maybe, is related with lower friction factor.

References

- 1) Müller-Steinhagen, H. (2000). Heat Transfer Fouling. Localized 14.02.03: <http://www.cpe.surrey.ac.uk/dptri/hms/fouling.htm>
- 2) Evaluation of the principles of magnetic water treatment. American Petroleum Institute, Washington DC, 1985. (API Publication 960).
- 3) Gamayunov, N.I. Enlargement of particles in water streams under the influence of crossed electric and magnetic fields. *J.Appl.Chem.*, 57, 1984.
- 4) Baker, J.S., Judd, S.J. Magnetic amelioration of scale prevention. *Wat.Res.*, 30, 1996.
- 5) Parsons, S.A., Wang, B.L., Judd, S.J., Stephenson. T. Magnetic treatment of calcium carbonate scale-effect of pH control. *Wat.Res.*, 31, 1997.
- 6) Quinn, C.J. Magnetic treatment of water prevents mineral build-up. *Iron and Steel Engineer*, 74, 1997.
- 7) Barrett, R.A., Parsons, S.A. The influence of magnetic fields on calcium carbonate precipitation. *Wat.Res.*, 32, 1998.
- 8) Coey, J.M.D, Cass, S. Magnetic water treatment. *J.Magn.Magn.Mater.*, 209, 2000.
- 9) Gabrielli, C., Jaouhari, R., Keddam, M. Magnetic water treatment for scale prevention. *Wat.Res.*, 35, 2001.
- 10) Kobe, S., Drazic, G., McGuiness, P.J., Strazisar, J. The influence of the magnetic field on the crystallization form of calcium carbonate and the testing as a magnetic water-treatment device. *J.Magn.Magn.Mater.*, 236, 2001.
- 11) Hewitt, G.F., Shires, G.L., Bott, T.R. Process heat transfer. CRC Press, Boca Raton, 1994.
- 12) Hasson, D., Bramson, D. Effectiveness of magnetic water treatment in suppressing CaCO_3 scale deposition. *Ind.Eng.Chem.Process Des. Dev.*, 24, 1985.
- 13) Bockris, J.O.M., Reddy, A.K.N. Modern electrochemistry, vol. 2A, 2nd Ed., New York, Kluwer Academic/Plenum Publishers, 2000.